Fuel Cycle Energy Conversion Efficiency Analysis

Status Report

25 May 2000

PREPARED FOR

California Energy Commission
Transportation Technology and Fuels Office
1516 Ninth Street, MS-41
Sacramento, CA 95814

and

Air Resources Board
Research Division
2020 L Street
Sacramento, CA 95812

Prepared by:
Stefan Unnasch
Louis Browning
ARCADIS Geraghty & Miller, Inc.
555 Clyde Avenue
Mountain View
California 94043

1. SUMMARY

This report provides the basis of the proposed analysis of fuel cycle energy conversion efficiency and related carbon dioxide emissions and preliminary results for the Phase 1 activities. This project defines the "fuel cycle" as "well to wheels". It includes extraction of fuel feedstocks, production of the fuel, storage and transportation of the fuel to a local distribution station, distribution to vehicles at a local distribution station, and consumption of fuel in the vehicle. It does not include vehicle criteria pollutant emissions, or the energy to produce or recycle a vehicle. This project builds upon a previous ARB study performed in 1996, "Evaluation of Fuel Cycle Emissions on a Reactivity Basis", but focuses on energy conversion efficiency and greenhouse gas generation during the fuel cycle. With this and other information, California Air Resources Board (ARB) staff can determine the value of partial ZEV credits for super ultra low-emission vehicles (SULEVs) in terms of greenhouse gas emissions and California Energy Commission (CEC) staff can determine energy demands and greenhouse gas generation from various fuel and vehicle technologies. The document, herein, will evolve into the final report. It provides a discussion of fuels and scenarios for this study as well as differences in energy conversion efficiencies that affect the scenarios.

1.1 PROJECT OBJECTIVE

The primary objective of this study is to determine the fuel cycle energy conversion efficiency and associated energy impacts of fuel and vehicle technology combinations being pursued over the next ten years. Specifically, energy conversion efficiency of a fuel is determined for the fuel production and energy conversion portions of the fuel cycle, including fuel acquisition and refining, distribution, refueling, and in-vehicle consumption. The selected vehicle fuels are reformulated gasoline (California Phase 2 and 3), diesel fuel (both conventional and synthetic), naphtha, compressed and liquefied natural gas (CNG and LNG), ethanol, and liquefied petroleum gas (LPG) for internal combustion vehicles, and methanol, compressed and liquefied hydrogen (CH_2 and LH_2), and naphtha for fuel-cell powered vehicles. In addition, hybrid technologies are investigated. This fuel cycle energy conversion efficiency is compared to that from electricity generation for electric vehicles. The energy conversion efficiency and CO_2 mass emissions are quantified for each fuel and for each phase of the fuel cycle. Energy and CO_2 emission estimates are made for 1996 as a base year and for the year 2010 based on four comparison cases. These comparison cases are made up of permutations of two different projection scenarios for each fuel (one pessimistic and one optimistic) and two different vehicle fuel economy cases. The uncertainty associated with energy conversion efficiency from every step of each fuel cycle will be estimated in the final report and those uncertainties will be propagated to develop an overall uncertainty for each fuel.

The following sections discuss and review the methods used to estimate and calculate the fuel cycle energy conversion efficiency and describe differences between energy conversion efficiency scenarios.

1.2 PROJECT APPROACH

The fuel cycle energy conversion efficiency associated with production and distribution of California Phase 2 and Phase 3 reformulated gasoline (CARFG2 and CARFG3), diesel fuel, synthetic diesel, naphtha, methanol, ethanol, LPG, CNG and LNG, CH_2 and LH_2, and electricity is evaluated, based upon production from one or more feedstocks. Gasoline, diesel fuel, synthetic diesel fuel, naphtha, CNG, LNG, ethanol, and LPG are considered for use in internal combustion engine or hybrid vehicles. Electricity is assessed for pure ZEVs (battery-only electric vehicles). CARFG3, naphtha, and methanol (with an on-board reformer), and CH_2 and LH_2 are considered for use in fuel cell vehicles.

The following outline summarizes the steps is used in this project:

- Determine the physical characteristics and properties of all the fuels and feedstocks
- Evaluate the lower heating value of the fuels and feedstocks, as well as the CO_2 emissions from combustion of fuel production equipment
- Outline scenarios for the production and distribution of fuels
- Determine representative vehicle classes for evaluation and comparison
- Evaluate fuel economy for candidate vehicle technologies
- Determine the energy conversion efficiency and CO_2 emissions for the processes involved with each scenario
- Develop per-gallon fuel cycle energy conversion and CO_2 emissions estimates
- Compare fuel cycle energy conversion efficiencies and CO_2 emissions on a per mile basis using vehicle fuel economies

1.3 REPORT SCOPE

Table 1 summarizes the fuel/feedstock combinations that are considered in this study. As indicated in the table, several fuel/feedstock combinations are complicated by the fact that several products are made from the same feedstock and most fuels can be produced from several feedstocks. Different mixes of feedstocks are also used in fuel production. For example, a variety of crude oil sources make up the feedstock for California refineries, and this mixture will change in the future. Methanol is currently produced from natural gas, while production from biomass has been considered as options for the future. Natural gas is produced from gas fields as well as a byproduct of oil production, and the gas can be used for many purposes, including the manufacture of synthetic liquid fuels or methanol. Synthetic diesel has been produced from remote natural gas and blended with commercial diesel fuel in California. LPG is produced during oil refining and derived from natural gas liquids, a product of natural gas production. Electricity can be produced from a myriad of feedstocks, which range in CO_2 impact from solar energy to coal. Diesel, LPG, methanol, and electricity were already evaluated in the 1996 study. The assumptions for these fuels were reevaluated. Additional power generation assessments were performed for electric power generation. Further attention was paid to assumptions that affect energy conversion efficiency in the South Coast Air Basin (SoCAB) as about half of California's vehicle population and associated energy use is there.

Fuel cycle energy conversion efficiency is analyzed over a range of assumptions. The major factors that affect fuel cycle efficiency in this study include the efficiency of fuel conversion technologies, fuel and feedstock transportation modes and distances, and vehicle fuel economy. Other factors that affect fuel cycle energy impacts such as fuel transport equipment fuel consumption, leaks, spillage, and feedstock extraction energy inputs are also considered.

Table 1. Fuels, feedstocks, and refining processes evaluated in this study

Feedstocks	Processes	Fuels
Crude Oil	Oil refinery operations	Conventional Gasoline, Reformulated Gasoline CARFG2, CARFG3 Diesel, reformulated diesel LPG Naphtha
Natural gas, Coal, Biomass, Waste Materials	Steam reforming/ methanol synthesis Gasification or other process	Methanol
Corn, Biomass, Waste Materials	Fermentation	Ethanol
Natural gas	Gas stripping and treatment	CNG, LNG LPG
Natural gas	Reforming, FT synthesis	Synthetic diesel Naphtha
Natural gas, Biomass, Solar Energy, Electricity	Reforming, Gasification, Electrolysis, Liquefaction	CH_2, LH_2
Crude oil, Natural gas, Coal, Biomass	Utility boilers, Cogeneration facilities, Non-fossil power	Electricity

The general fuel processing steps associated with fuel production and distribution are categorized into eight phases shown in Table 2. These phases are grouped into the following: extraction, production, marketing, and distribution; which are later used for presenting the results of the study.

Table 2. Fuel cycle production and distribution phases

Phase No.	Description
Extraction	
1.	Feedstock extraction
2.	Feedstock transportation
Production	
3.	Fuel processing/refining
Marketing	
4.	Fuel storage at processing site
5.	Transport to bulk storage
6.	Bulk storage
7.	Transport to local distribution station
Distribution	
8.	Local station distribution

2. DEFINITION OF FUEL CYCLES

This study considers fuel cycle conversion efficiency and CO_2 emissions from various vehicle fuels. For the purposes of this study, fuel cycle emissions represent fuel extraction, production, distribution, and vehicle conversion. This definition is often referred to as "well to wheels".

Emissions of greenhouse gases from vehicle exhaust and energy conversion efficiency of the vehicle are calculated directly from vehicle fuel economy, carbon weight percentage of the fuel, fuel energy, and fuel density.

Many of these fuels can be produced from several feedstocks. The analysis considers the marginal, or incremental gallon (or equivalent fuel unit) consumed in the SoCAB. In order to help evaluate the impact on local energy requirements, the energy used will be geographically categorized in the final report. Energy needed for fuel production in the South Coast Air Basin will also be sorted to count sources that correspond to incremental fuel production.

Table 3 shows the fuel/feedstock combinations considered in this study. The codes that correspond to the fuels and feedstocks are used later to identify energy conversion efficiencies in a database. For example, methanol from natural gas is considered separately from methanol from biomass, while a combination of feedstocks is considered for electricity production. Some fuel/feedstock combinations, such as methanol from natural gas, were represented separately while others were combined to simplify the comparison of processes such as crude oil shipments. The analysis will be completed in two phases with the Phase 1 completed in 2000 and Phase 2 completed in 2001. The fuels initially evaluated in light-duty vehicle applications in Phase 1 are indicated in Table 3. Further analysis in heavy-duty vehicles and the use of other fuels will be performed in Phase 2.

Table 3. Feedstock/fuel combinations considered in this study

Feedstock	Code	Fuel	Code	Vehicle[a]	Phase[b]
Crude Oil	o	Reformulated Gasoline	R2, R3	IC, HEV, ATR/PEMFC	1
Crude Oil	o	Diesel, clean diesel	D	IC, HEV	1
Crude Oil	o	LPG	P	IC	2
Crude Oil	o	Naphtha	N	Scenarios 2 & 3: ATR/PEMFC	1
Natural Gas	n	CNG	C	IC	1
Natural Gas	n	LNG	L	IC	2
Natural Gas	n	LPG	P	IC	2
Natural Gas	n	Synthetic Diesel	F	IC, Scenario 3: HEV	2
Natural Gas	n	Methanol	M	Scenarios 2 & 3: SR/PEMFC	1
Natural Gas	n	Compressed Hydrogen	CH_2	PEMFC	1
Natural Gas	n	Liquefied Hydrogen	LH_2	PEMFC	1
Natural Gas	n	Naphtha	FN	Scenario 2& 3: ATR/PEMFC	1
Biomass	b	Methanol	M	Scenario 1: IC, Scenarios 2 & 3: SR/PEMFCCell	1
Biomass	b	Ethanol	E	IC	1
Various	x	Electricity	J	Battery Only Electric Vehicle	1

[a] IC= internal combustion engine, HEV= hybrid electric vehicle, ATR= autothermal reformer (fuel processor that converts air, steam, and fuel to hydrogen), PEMFC= proton exchange membrane fuel cell, SR = steam reformer.

[b] Phase 1 analysis to be complete in 2000. Phase 2 completed in 2001. Heavy-duty vehicles included in Phase 2

2.1 SCENARIOS

Energy conversion efficiency and CO_2 emissions are estimated for conditions in 1996 and 2010 with technologies and vehicle fuel economy consistent with these time periods. The fuel processing scenarios in this study, identified as Scenarios 1 through 3, represent energy conversion efficiency for the years 1996 and 2010. Scenario 1 represents energy conversion efficiency for the base year, 1996. The two scenarios for year 2010 represent a high and low estimate based on technology and feedstock assumptions. Table 4 shows the fuel processing scenarios explored in this study. The assumptions for each fuel-processing scenario correspond to parameters in the subsequent discussion. Vehicle fuel economy cases are discussed later in Table 10.

Table 4. Scenarios and timing for fuel production and distribution

Scenario	Year	Description
1	1996	Current technologies. Equipment meets prevailing standards. SoCAB refinery emissions based on 1996 inventory in 1997 AQMP.
2	2010	Equipment meets standards applicable in year 2010. Refinery emissions adjusted from 1996 inventory for local rules. Emissions consistent with ARB factors for fuel distribution. Currently available fuel production and distribution processes. Highest marginal energy and emissions impact.
3	2010	Same as Scenario 2. Lower assumptions on distribution emissions. New alternative fuel production facilities and technologies. Lowest marginal energy and emissions impact.

Some of the factors that affect energy conversion efficiency include the location of feedstocks, emission control assumptions, and marginal energy conversion efficiency considerations. Tables 5, 6, 7 and 8 identify key assumptions that affect fuel cycle emissions and efficiency. A variety of assumptions affect fuel cycle energy inputs. These include the efficiency of fuel production processes, efficiency of other equipment in the fuel cycle, fuel transport distances, equipment leaks and other losses, and end use vehicle fuel consumption. Key assumptions that affect fuel cycle energy are the efficiency of fuel conversion processes as well as the modes and distances for fuel transport. While the energy consumption of equipment such as delivery trucks, oil tankers, and compressors is an important input to a fuel cycle analysis, the energy use per unit of work (efficiency) is well known and subject to less uncertainty than other assumptions. The location of feedstock resources and the distance required for transport to California has a significant effect on fuel cycle energy inputs. The mix of fuel production equipment also has an important impact, as some equipment is more efficient than others are.

This study is intended for use in evaluating incremental energy conversion efficiency from fuel production as well as average energy conversion efficiency. The focus on marginal energy conversion efficiency raises questions of transporting energy into and out of the state. For example, methanol could be sold for vehicle use in the South Coast Air Basin without any production energy conversion affecting local energy use. Similarly, gasoline is transported to other states from the South Coast Air Basin while the refinery energy conversions contribute to energy losses in the South Coast Air Basin.

Table 5. Petroleum Refinery Energy

	Crude	Electric	Refinery Fuel	Alcohol
Fuel	gal/gal	kWh/gal	Btu/gal	Content
RFG2	0.87	0.23	13,600	6.8% methanol
RFG3	0.93	0.26	14,000	5.8% ethanol
Diesel	1.03	0.11	5,200	None
LPG	0.71	0.05	7,100	None

Table 6. Methanol, Hydrogen, Natural Gas Production

Process	Scenario	Efficiency	Feedstock
Methanol from natural gas	2	68.3%	Natural gas
	3	72.3%	80% NG, 20% Remote NG
Methanol from landfill gas	2	57.0%	Landfill gas, displace power
	3	57.0%	New landfill gas
Methanol from biomass	2	51.0%	Forest material
	3	63.0%	Forest material
Hydrogen local reformer	2	64.0%	Natural gas
	3	65.0%	Natural gas, export steam
Hydrogen central reformer	2	73.0%	Natural gas
	3	83.0%	Natural gas
Hydrogen electrolysis	2	68.0%	Electric power
	3	72.0%	Electric power
CNG from natural gas	2	91.0%	Natural gas
	3	91.0%	Natural gas

Table 7. Ethanol Production

		Feedstock	Electric	Process Fuel
Process	Scenario	Consumption	kWh/gal	Btu/gal
Ethanol from	2	2.6 bushels/gal	2.1	47,000 coal/NG
corn	3	2.6 bushels/gal	1.5	39,000 coal/NG
Ethanol from	2	77.4 gal/ton	-3.6	Lignin
woody biomass	3	91.5 gal/ton	-2.1	Lignin
Ethanol from	2	81.7 gal/ton	1.2	28,600 NG
waste paper	3	98.9 gal/ton	1.1	25,000 NG

Table 8. Transportation distances based on moving fuels and feedstocks to California

Fuel/Feedstock	Location	Average Distance	Mode
Crude Oil	Indonesia	8790 miles	Ship
Methanol, FT Diesel	Indonesia	8790 miles	Ship
Natural Gas	Southwest U.S., Canada	1070 miles	Pipeline
LPG	Southwest U.S., Canada	1070 miles	Rail
Ethanol — biomass	California	90 miles	Truck
Ethanol — corn	Midwest	3370 miles	Rail, Barge

2.2 ELECTRIC POWER GENERATION MIX

Calculations for electric vehicles and grid connected HEVs will be performed for different power generation mixes. For California, the marginal power generation mix is also presented. This generation mix includes power plants that would come on-line for night time charging of electric vehicles and is considered by State agencies to be the most relevant when considering emission or energy impacts. Table 9 shows the assumptions for this night time generation mix.

Table 9. Electricity Production

Process	Scenario	Heat Rate Btu/kWh	Efficiency	Transmission Losses	Feedstock
Combined cycle	2	8,770	39%	9%	Natural gas
power plant	3	8,050	42%	7%	Natural gas
Green power	3	12,500	27%	7%	60% biomass
					40% non combustion (PV, hydro, geothermal, wind)

2.3 FUEL ECONOMY CONSIDERATIONS

Table 10 shows vehicle fuel economy assumptions for a set of fuel economy cases that will provide a range of estimates when combined with different fuel cycle scenarios. Fuel economy is estimated from a baseline vehicle fuel economy that represents on-road driving.

Since it is not possible to obtain fuel economy test data for a consistent set of vehicles with similar attributes, fuel economy is estimated from energy efficiency data and the fuel's heating value. Fuel economy for alternative vehicles is estimated from the energy efficiency ratio (EER). The EER is the ratio of baseline gasoline vehicle energy consumption to the alternative vehicle energy consumption (on a lower heating value basis). This value is verified with data from various studies and vehicle tests.

EER values can be compared for different vehicles where the baseline and alternative vehicle are ideally identical models. The EER reflects the change in efficiency of one drive train over another powered by a different fuel with other vehicle attributes such as weight and aerodynamics held constant. EER values are determined for various vehicle combinations and used to determine the fuel economy for a consistent vehicle or mix of vehicles.

For example, if a diesel car operates with a fuel economy of 33 mpg and a similar gasoline vehicle operates with a fuel economy of 24.9 mpg, the energy consumption is 2260 kJ/km for the diesel vehicle and 3000 kJ/km for the gasoline vehicle. The energy efficiency ratio would be 1.33.

Figure 1 shows the range of fuel economies for the vehicle technologies and fuels considered in Phase 1 as fuel economy cases b and c.

Table 10. Light-duty vehicle fuel efficiency assumptions

	EER		mpeg			
			Case b	Case c	Case d	Case e
Gasoline,RFG ICE	1.00	1.00	30.2	30.2	45.2	45.2
Diesel, FTD DI CI	1.21	1.37	36.5	41.3	54.7	62.0
RFG HEV	1.30	1.45	39.2	43.7	58.8	65.6
CNG, LPG ICE	0.98	1.08	29.6	32.6	44.3	48.9
E85 ICE FFV	1.03	1.09	31.1	32.9	46.6	49.3
RFG, Naptha PEMFC	0.97	1.35	29.3	40.7	43.9	61.1
Methanol SR/PEMFC	1.39	1.54	41.9	46.5	62.9	69.7
Hydrogen PEMFC	1.50	1.74	45.2	52.5	67.9	78.7
Battery EV	2.40	2.90	72.4	87.5	108.6	131.2

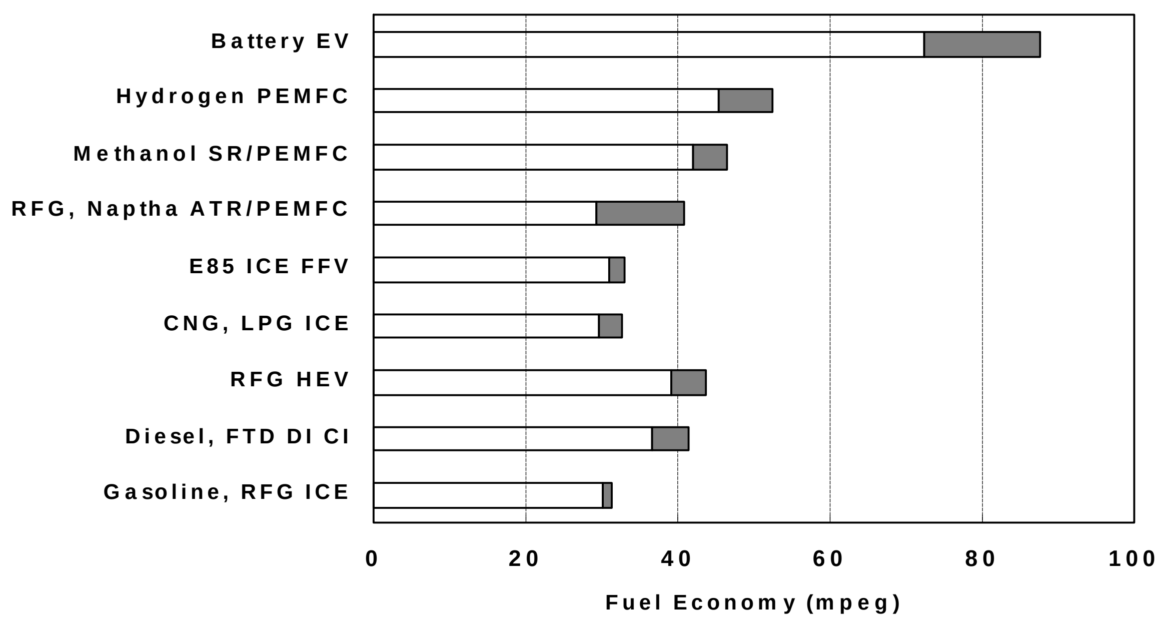

Figure 1. Fuel Economy Case b and c Comparison

2.4 Comparison of Fuel Cycle Impacts

Table 11 shows the range of cases that encompass the likely outcomes for fuel cycle energy and CO_2 emissions. A range of assumptions for fuel cycle processes is previously presented with scenarios 1, 2 and 3. Vehicle fuel economy assumptions are represented with assumptions a, b, c, d, and e. These assumptions are combined to provide a set of comparisons labeled as Cases A, B, C, and D. As indicated in Table 7, Case B represents the range of assumptions for fuel cycle scenarios 2 and 3 and fuel economy assumptions b, and c. Similarly, Case D is based on a higher fleet average fuel economy. The mix of vehicles for cases A, B, and D represent conventional vehicles that are sold in the market. EPA publishes data on vehicle size and fuel economy classifications. This data or California specific data is used to estimate the average fuel economy for new vehicle purchases. This vehicle distribution is used to estimate alternative vehicle purchases.

Case C considers a market shift for alternative technologies. Alternative vehicle technologies may be sold in different vehicle size classes than conventional technologies. The mix of vehicles may vary from the distribution of conventional vehicles in the market. For example, CNG vehicles are often produced in the utility vehicle and truck categories. For a fleet that has decided to purchase CNG vehicles, they may be required to purchase a heavier vehicle than they would normally because of limited selection of CNG vehicles in smaller vehicle classes.

Alternately, if a fleet has decided to purchase electric vehicles, they may be required to purchase a smaller class vehicle than they would normally because of limited selection of electric vehicles in larger vehicle classes. The effect on fuel cycle emissions and energy consumption is affected by the mix of CNG and electric vehicles as well as other technologies which are estimated in Case C. In this Status Report, the results for Case b are presented.

Table 11. Cases for comparing fuel cycle energy impacts

Cases for Comparison	**Range of fuel cycle, fuel economy assumptions**
A. 1996. Baseline	Scenario 1a Standard vehicle distribution
B. 2010. Nominal improvements in vehicle fuel economy. Alternative vehicle is similar to fleet average	Scenario 2b, 2c, 3b, 3c Standard vehicle distribution
C. 2010. Nominal improvements in vehicle fuel economy. Alternative vehicle mix is shifted to reflect market share	Scenario 2b, 2c, 3b, 3c Vehicle distribution shifted for vehicle type
D. 2010. Significant improvement in vehicle fuel economy. Alternative vehicle is similar to fleet average	Scenario 2d, 2e, 3d, 3e Standard vehicle distribution

3. MARGINAL ENERGY CONVERSION EFFICIENCY CONSIDERATIONS

Marginal energy conversion efficiency looks at the effect of new fuels or changes in fuel use. Often the question of how the marginal fuel is produced can affect the results of the study. The following are some marginal energy conversion efficiency considerations for this study:

<u>Petroleum production issues</u>

- Alternative fuels displace refinery imports
- Marginal crude oil imports from foreign sources
- Differences between petroleum production based on refinery model results
- RFG3 contains 5.8% ethanol
- RFG2 contains 11% MTBE

Electric power generation mix

- Most EV charging occurs at night time
- Marginal generation from new natural gas combined cycle plants
- Renewable production capacity is a small percentage of total new capacity
- Hydroelectric resources are fully utilized

4. RESULTS

In this status report, the results for Fuel Production Scenario 3 and Fuel Economy Cases b and c are presented. The other results for Phase 1 of the analysis will be included in the final report.

The following figures describe the amount of energy used across the entire fuel cycle to power the different vehicle technologies on a per mile basis. Additionally, figures show the amount of energy derived from fossil fuel feedstocks on a per mile basis. Lastly, figures illustrate the amount of CO_2 emissions generated on a per mile basis.

4.1 Energy Consumption Results

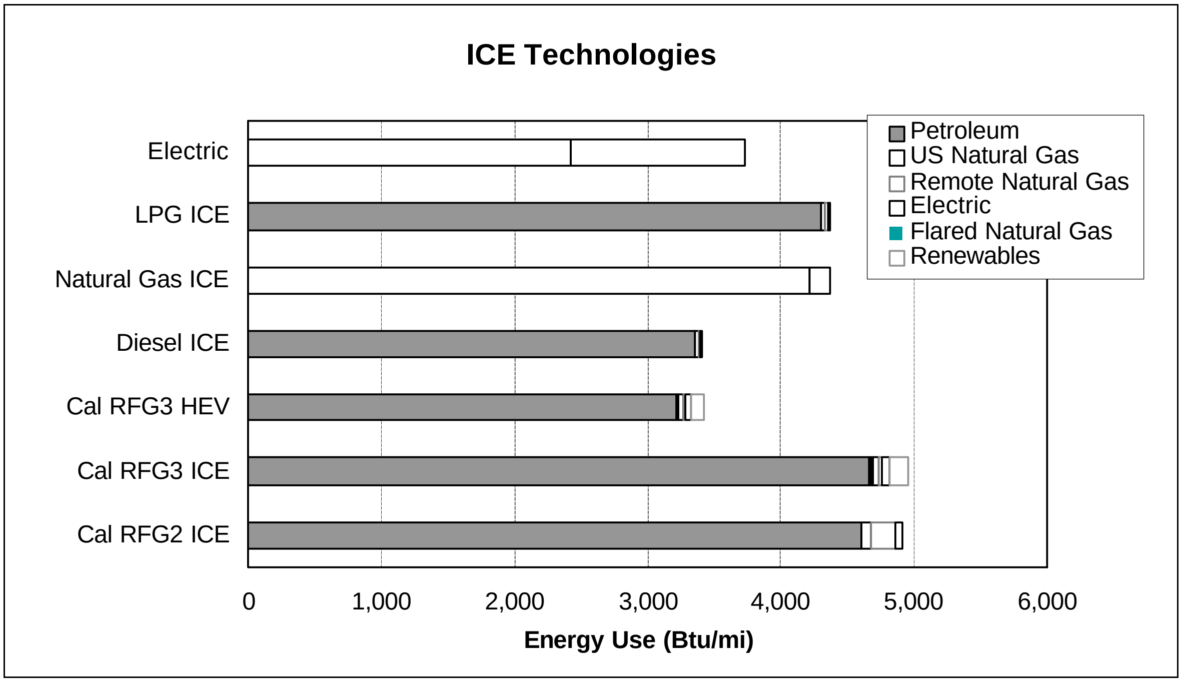

Figure 2. ICE Technologies-Energy Resource Mix Comparison (Scenario 3c)

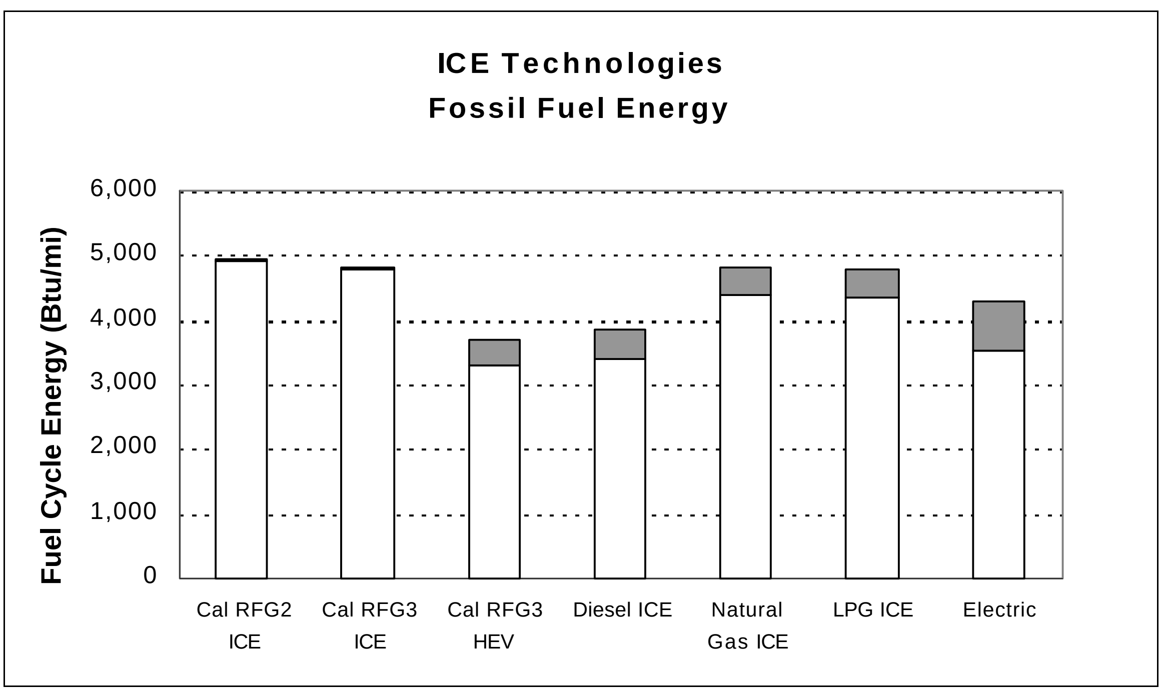

Figure 3. ICE Technologies - Energy Efficiency Comparison (Scenarios 3b & 3c)

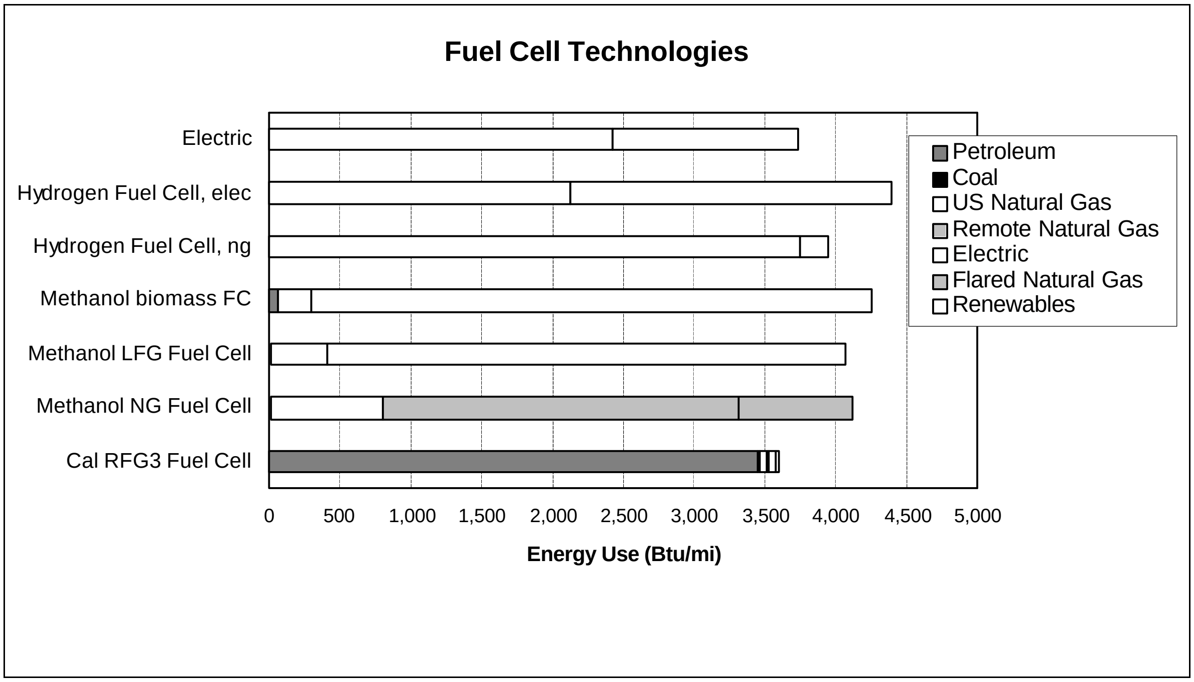

Figure 4. Fuel Cell Technologies - Energy Resource Mix Comparison (Scenario 3c)

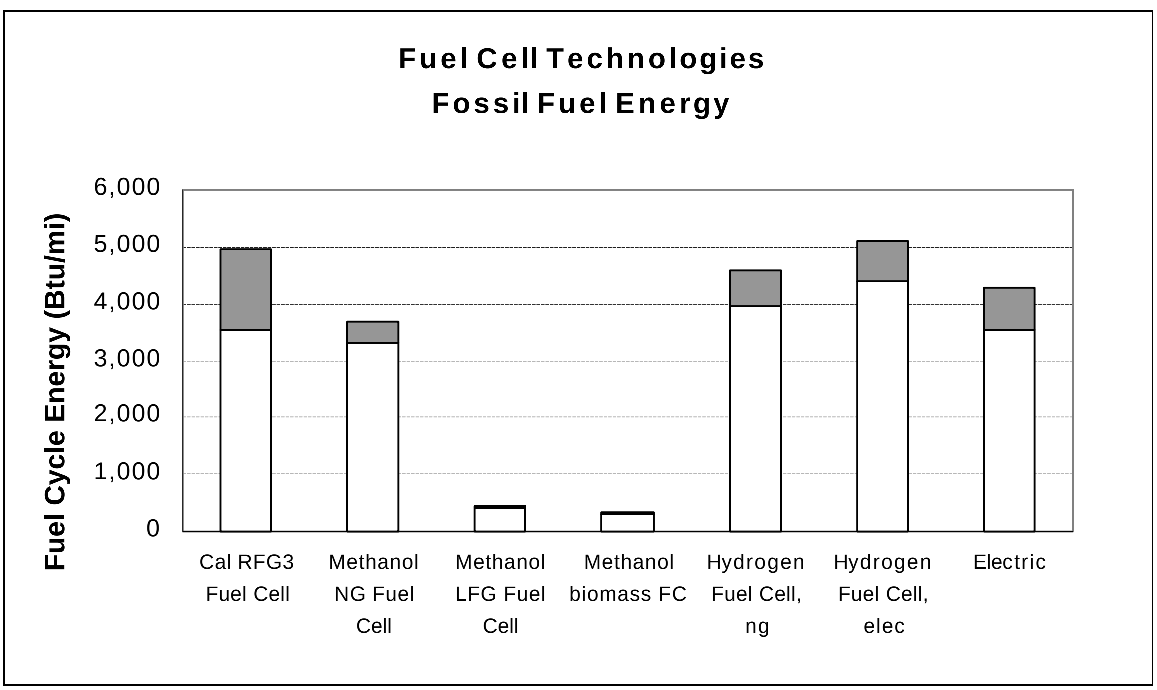

Figure 5. Fuel Cell Technologies - Fossil Fuel Energy Efficiency Comparison (Scenarios 3b & 3c)

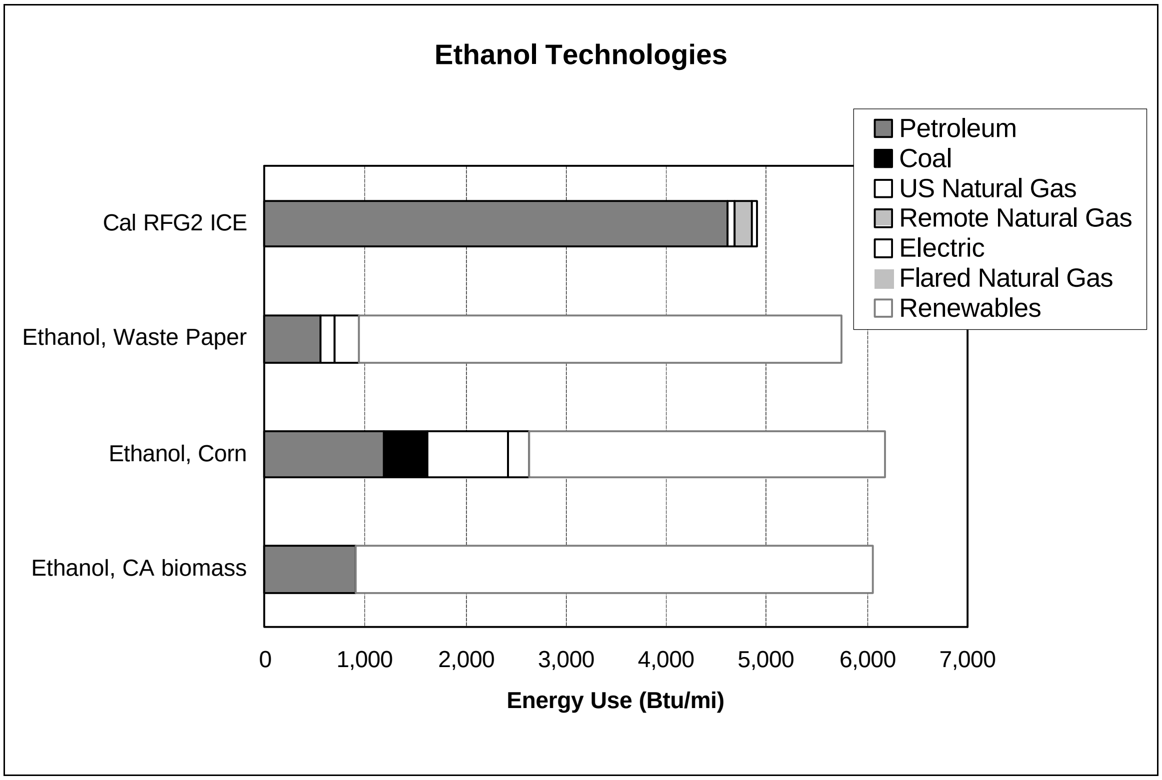

Figure 6. Ethanol Technologies - Energy Resource Mix Comparison (Scenario 3c)

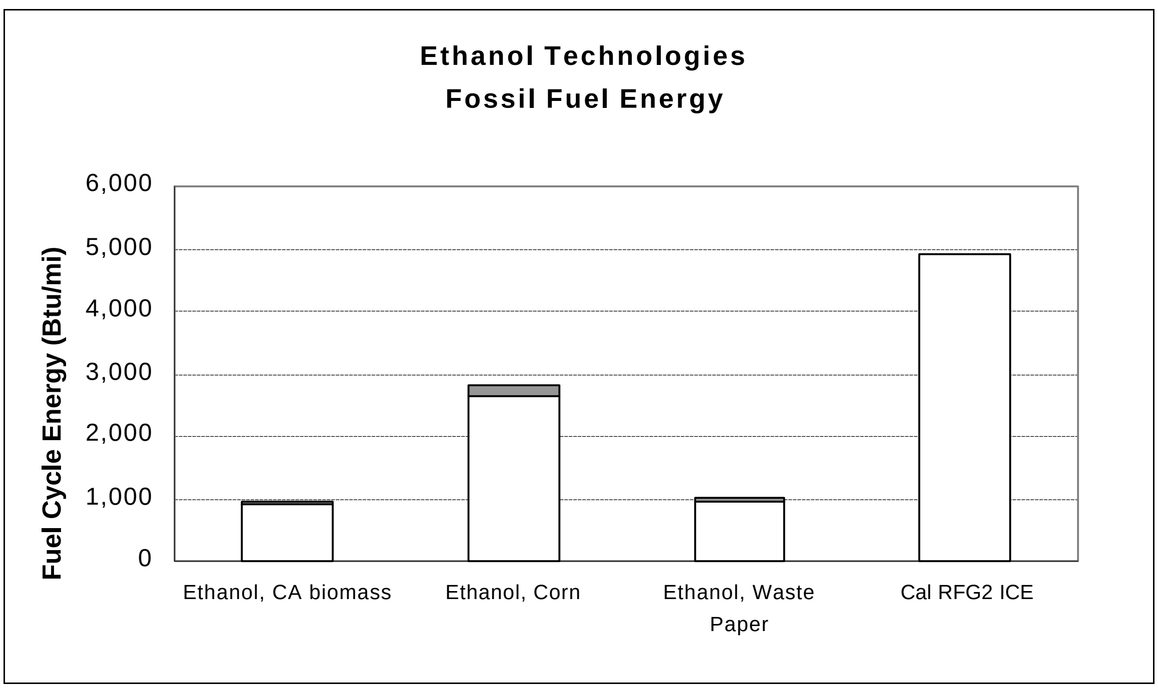

Figure 7. Ethanol Technologies - Energy Efficiency Comparison (Scenarios 3b & 3c)

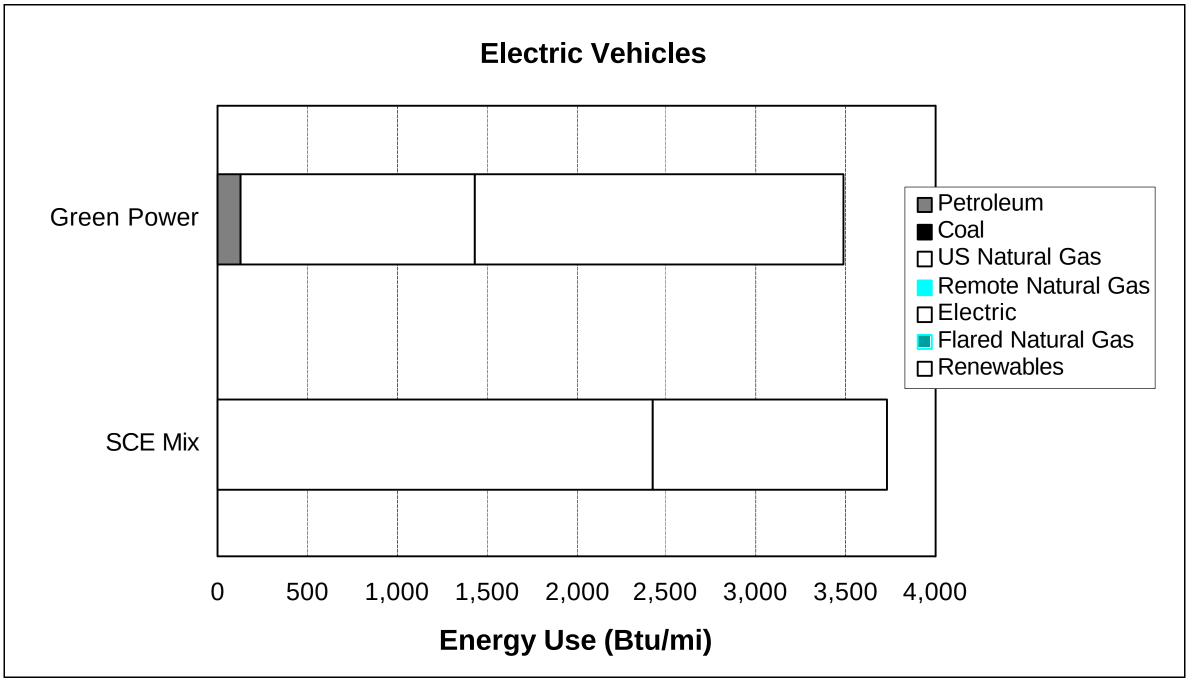

Figure 8. Renewable Electricity - Energy Resource Mix Comparison (Scenario 3c)

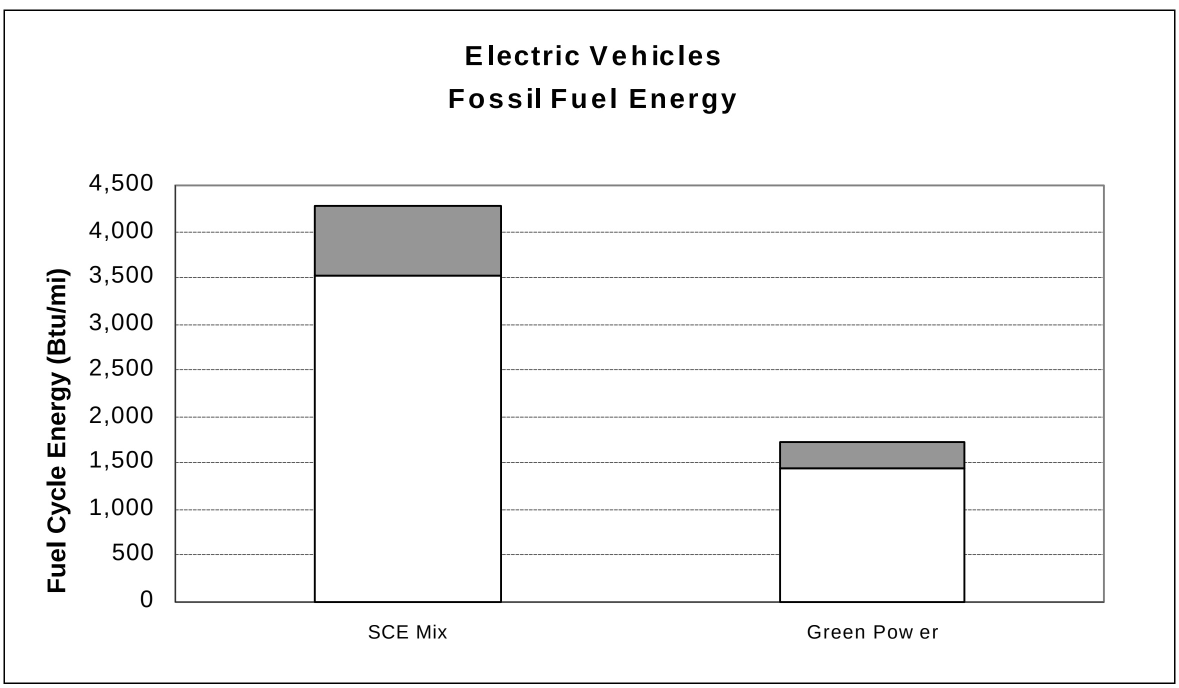

Figure 9. Renewable Electricity - Energy Efficiency Comparison (Scenarios 3b & 3c)

4.2 CO_2 Emissions Results

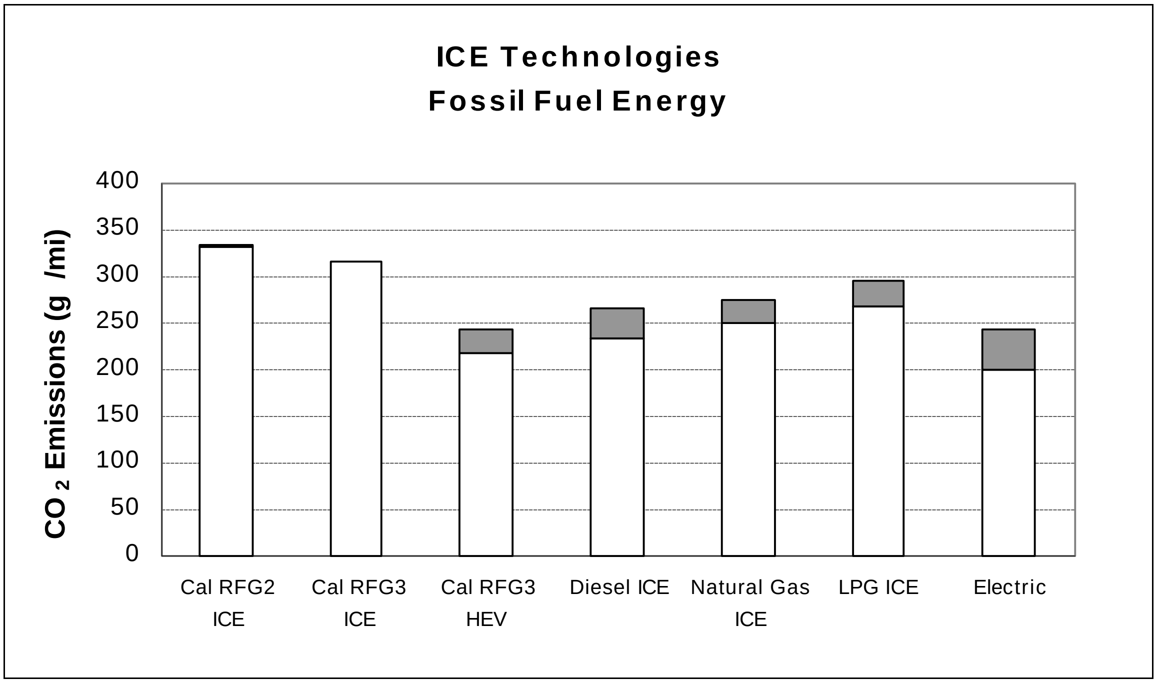

Figure 10. ICE Technologies - CO_2 Comparison (Scenarios 3b & 3c)

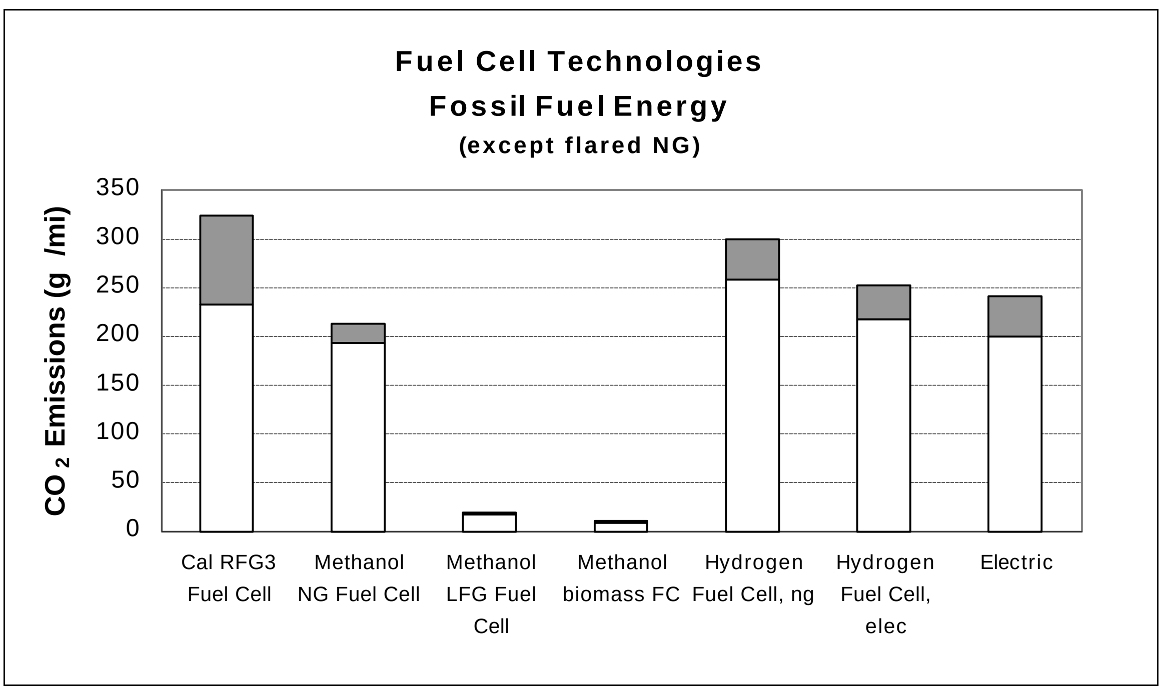

Figure 11. Fuel Cell Technologies - CO_2 Comparison (Scenario 3b & 3c)

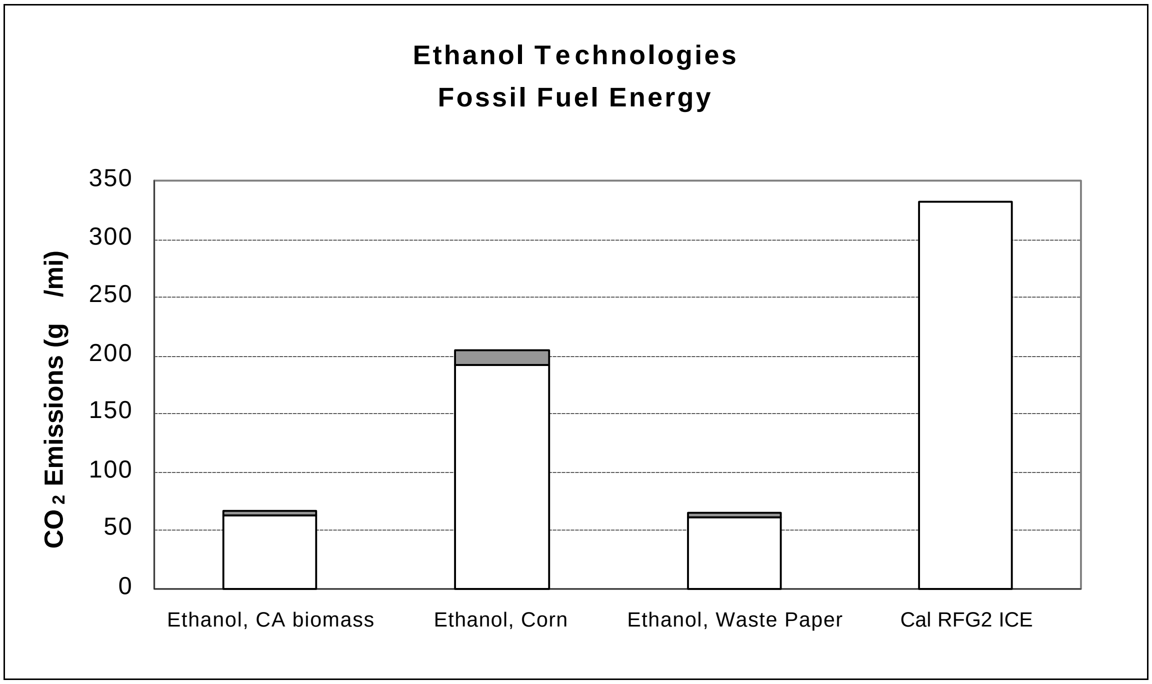

Figure 12. Ethanol Technologies - CO_2 Comparison (Scenario 3b & 3c)

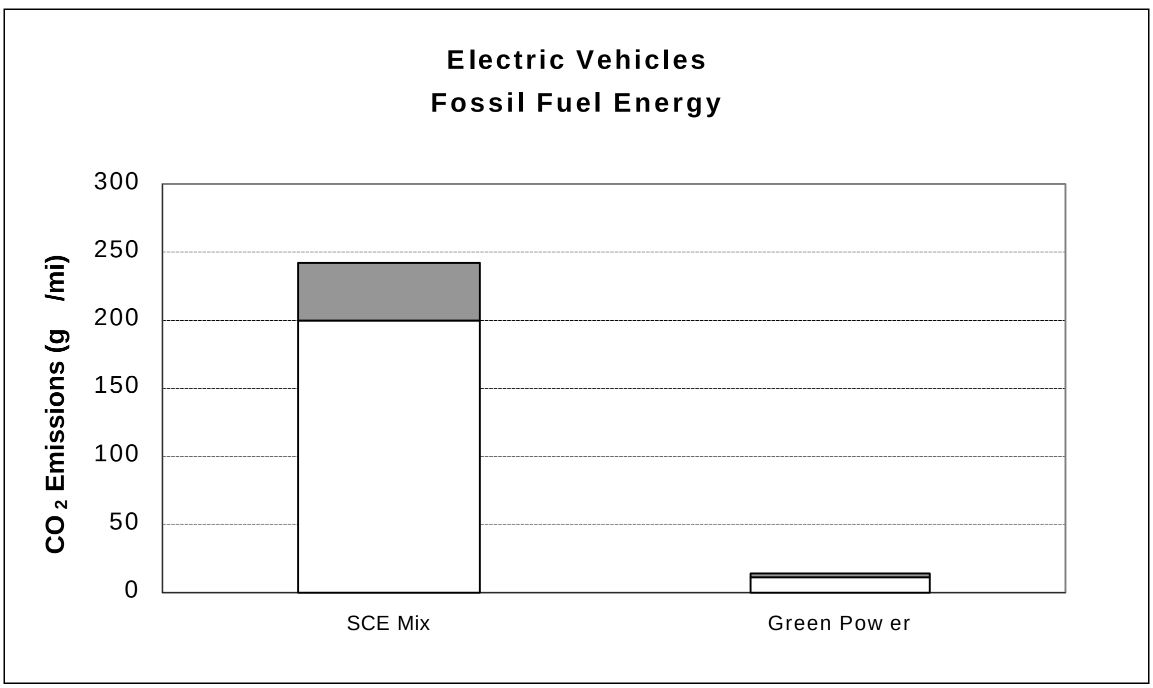

Figure 13. Renewable Electricity - CO_2 Comparison (Scenario 3b & 3c)

5. CONCLUSIONS

There are several general conclusions to be drawn from the analysis for Scenario 3b and 3c that are listed below.

- Vehicle energy consumption has the largest effect on total fuel cycle and vehicle energy and CO_2 emissions.
- Energy demand and CO_2 emissions for EVs are strongly driven by new CA generation mix.
- Marginal energy assumptions are consistent with electric power generation mix from new natural gas combined cycle power plants. These assumptions result in higher fossil CO_2 than the average CA generation mix but lower CA emissions.
- RFG3, if made with ethanol, would require slightly less fossil energy than RFG2.
- Fuel cell technologies, electric vehicles, and gasoline HEVs result in similar CO_2 emissions.